UDC 620.18:621.7.018.1
DOI: 10.37128/2520-6168-2024-4-1

METALLOGRAPHIC STUDY OF CHANGES IN THE STRUCTURE OF A DEFORMED METAL LAYER DURING WATER-PULSE SMOOTHING

Yurii PALADIICHUK, Candidate of technical sciences, Associate professor
Inna TELIATNYK, Recipient of the Third Educational and Scientific Level
Maryna KUBAI, teacher
Vinnytsia National Agrarian University

ПАЛАДІЙЧУК Юрій Богданович, к.н.т., доцент,
ТЕЛЯТНИК Інна Анатоліївна, здобувач третього освітньо-наукового рівня
КУБАЙ Марина Григорівна, викладач
Вінницький національний аграрний університет

When materials are processed under static or impact loads, a tool imprint is first formed, which is later transformed into a series of interlocking marks. When a hard ball is pressed into a material, the initial elastic deformation turns into plastic deformation as the load increases. Plastic deformations propagate, leaving an imprint whose size depends on the properties of the material being processed.

The microhardness of a material is an important indicator of its resistance to indentation; higher values reduce the size of the imprints and the depth of deformation, increasing the durability of the material. The depth of the rivet, which depends on the depth of the print, is determined by a coefficient that varies depending on the processing conditions. The diameters of the imprints and the load on the ball are described by the Hertz and Meyer equations, which help to assess the nature of deformations in the elastic and plastic regions.

Machining processes that are affected by friction and material anisotropy are more complex, so the proposed equations are of limited use. Plastic deformation indicates the degree of hardening of the material, which varies depending on the structural components of the metal. In particular, martensitic steels exhibit a higher pitting depth compared to sorbitol.

Strain hardening goes through three stages: initiation of dislocations, their interaction and accumulation, and intensive displacement of dislocations. These stages are interrelated and affect the overall mechanical properties of metals. Grain boundary displacements play an important role during deformation at high temperatures, which can change the mechanical properties of the material.

Additionally, the study highlights the importance of understanding the microstructural changes induced by plastic deformation during surface treatment processes. By analyzing the interaction of elastic and plastic deformation, strain hardening mechanisms, and the effects of dislocation accumulation, the research provides insights into optimizing the mechanical properties of metals. These findings are essential for improving the durability, wear resistance, and strength of machined components, contributing to the development of more efficient and reliable surface treatment technologies.

Key words: *metallographic study, deformed metal layer, structural changes, water-pulse smoothing, metal surface treatment, plastic deformation, microstructure, mechanical properties of metals, pressure treatment, technological process.*

Eq. 9. Fig. 16. Ref. 10.

1. Problem formulation

A sample for metallographic examination of the metal structure is called a grind. Since metal microstructure is studied in reflected light, the surface of the grind must have a minimum deformed layer, be flat, have maximum reflectivity without scratches, and allow for the distinction of microstructure elements due to uneven light reflection or relief formation [1-3]. The grind should reflect the microstructure of the entire product or part of it, so it is important to choose the right part of the product and the location of the surface to be examined.

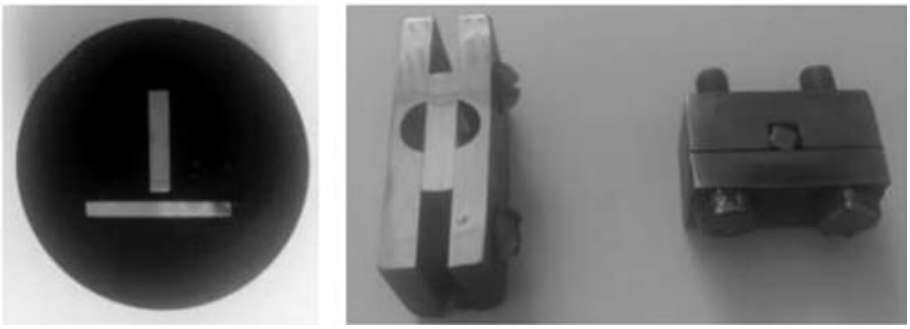
The microstructure of materials after plastic deformation is studied in the direction of deformation. Since the deformation can be uneven in different parts of the specimen, several specimens are cut along and across the direction of deformation.

For cast materials, the microstructure is determined by examining several grinds from different parts of the ingot: peripheral and central [1]. If the moulded product has different dimensions in different places (as in moulded steel), the microstructure is examined in all distinctive sections - from the largest to the smallest.

The microstructure of heat-treated alloys is examined in the surface and deep layers of the part. To analyse the microstructure of materials produced by powder metallurgy, several samples are taken from the central and peripheral parts of the pressed material.

Microanalysis is used to study the causes of parts failure during operation. [1,2]. Microanalysis is used to study the causes of parts failure during operation.

The surface area of the grinding wheel is typically around 1 cm², and the height of the sample should be at least 10 mm for ease of use. To produce grinds from smaller workpieces (e.g. tape, wire), they are placed in a cylindrical mandrel or filled with plastic after cutting (Fig. 1, a).



a) ***b)***

Fig. 1. Methods of fixing small samples in preparation for metallographic studies [1]: a – plastic mould, b – clamps of various shapes

In some cases, metal screw clamps are used to fix small samples (Fig. 1, b). These clamps provide reliable fixation of samples of various shapes and sizes, which allows them to be prepared for metallographic studies with high quality, while maintaining the integrity and accuracy of the surface [1,2].

2. Analysis of recent research and publications

Preparing a flat grinding surface is necessary for further analysis of the material's microstructure and involves several steps: cutting, levelling, grinding and polishing. All these operations are performed in such a way as not to cause changes in the microstructure of the metal [1-3]. Particular attention is paid to the first and second steps, as they should not be accompanied by deformation of the surface layers or heating of the sample. After preparation, the surface of the grind should be flat, smooth, free of scratches, pits and contamination, which ensures the reliability and accuracy of the results of metallographic examination.

The workpiece for the grinding wheel is usually cut using abrasive wheels, while the surface is levelled using lathes, milling machines or grinders. Saws, milling cutters, or incisors are used to process soft materials [1, 2]. In the case of high metal hardness, the sample is cut with carborundum, diamond or vulcanite wheels. To minimise surface deformation and sample heating at this stage of preparation, it is important to choose the right tool and processing mode, as well as to ensure intensive cooling of the workpiece and tool [1-3]. This preserves the integrity of the metal's microstructure and improves the quality of the prepared grind.

Grinding is performed to reduce irregularities on the surface of the sample. For this purpose, abrasive papers with different numbers are used, which indicate the grain size of the abrasive powder attached to the paper or cloth backing [1]. The sanding process begins with coarse-grit paper and gradually moves to finer grit. The sample is ground until all scratches from previous processing are completely removed. After each grinding step, the sample must be cleaned of abrasive residue and ground metal before moving on to a finer grit paper [2]. Usually, 4 to 5 abrasive paper numbers are sufficient. After grinding, the sample is thoroughly rinsed under running water and dried in preparation for further analysis.

It is important to avoid severe deformation when grinding soft non-ferrous metal samples, as this can adversely affect their microstructure. Additionally, abrasive particles that come off the abrasive paper can be pressed into the surface of metals along with metal chips, which also impairs the quality of the finish. [2,3]. To prevent this, it is important to regularly clean the abrasive paper of worn abrasive particles or use special protective materials.

For example, when used for aluminium grinders, the abrasive paper is waxed to reduce friction and prevent chip adhesion, resulting in a better finish. It is not only suitable for aluminium, but also for other soft metals that require gentle sanding [2,3]. The right choice of sample processing method and tools guarantees the preservation of their physical and chemical properties, which is important for further analysis.

Polishing is an important step in the preparation of the sample, as its purpose is to further reduce irregularities on the flat surface. This process is completed when all surface marks and scratches are completely removed and the sample has a mirror-like smoothness. If, despite prolonged polishing, traces of defects remain, the sample must be additionally processed with fine-grit sandpaper and then polished again [2-4].

Polishing can be performed using mechanical, electrolytic or chemical methods. The polishing process uses a variety of abrasives such as aluminium oxide, chromium oxide and other oxides. For hard materials, in particular, diamond powder paste or diamond wheels are used to provide a high level of finish and surface quality.

It should be noted that after polishing, the microstructure of the sample is usually impossible to detect, as the surface becomes very smooth [2-4]. However, there are exceptions, such as alloys where the structural components differ significantly in composition and hardness. In such cases, different areas of the grind are subjected to different degrees of polishing, which can lead to the formation of relief on the surface of the sample.

After polishing, regardless of the method chosen, the abrasive is rinsed with water and then treated with alcohol to remove any remaining abrasive particles. Finally, the sample is dried using filter paper, making it ready for further analysis. This is an important step, as the cleanliness and dryness of the sample surface play a key role in the accuracy of the metallographic results [2-4].

To reveal the macrostructure of the material, it is necessary to grind and polish the working surface of the sample with high quality. After completion of these steps, the prepared sample for macrostructural analysis is called a macro-grind. When viewed under a microscope, a macro-grind appears as a light circle on which dark areas - grey or black, and sometimes even yellow or other colours - can often be observed, usually of small size. These areas indicate the presence of non-metallic inclusions that may be the result of the manufacturing process or certain impurities in the alloy [2]. In some alloys, dark areas can be characteristic structural components.

In addition, the porosity of the material can be detected by examining the unetched macro-grind. Porosity is an indicator of the degree to which the volume of a material is filled with pores that occur during manufacturing or use. The presence of small cavities in the structure of the material may indicate deficiencies in the manufacturing technology or the impact of external factors on the material during its operation. The determination of porosity is important for assessing the mechanical properties of a material, as materials with a high degree of porosity usually have reduced strength and resistance to stress.

Thus, a high-quality macro-grind preparation not only reveals the macrostructure of the material, but also provides important information about its physical properties and potential defects, which can be useful for further analysis and application in various industries [2].

In order to study the microstructure of a material, it is first necessary to identify it. The process of microstructure detection typically involves creating a shallow relief on the polished surface of the sample, where the configuration of the bumps reflects the location and contours of individual crystallites. In some cases, this relief can occur directly during the polishing process. For example, during mechanical polishing, hard crystallites usually protrude on the surface, while soft components may be recessed [2].

In most situations, the relief is formed by etching - a short-term exposure to a reagent that causes selective dissolution or chemical change of the material. To do this, select the appropriate etchant and duration of etching, based on reference data or by conducting experiments. It is important that this process provides an accurate representation of the microstructure of the material, as this affects the subsequent quality of the analysis.

After successful completion of these procedures, the sample prepared for microstructural analysis is called a micrograin.

The micrograin should be clear enough to allow the researcher to observe and analyse the crystal structure under a microscope. The quality of the microgrit preparation directly affects the accuracy of the data obtained, so attention to detail at every stage - from polishing to etching - is critical to the success of microstructure analysis [2,3].

Micro-etching reveals two key characteristics of the microstructure of metals and alloys:

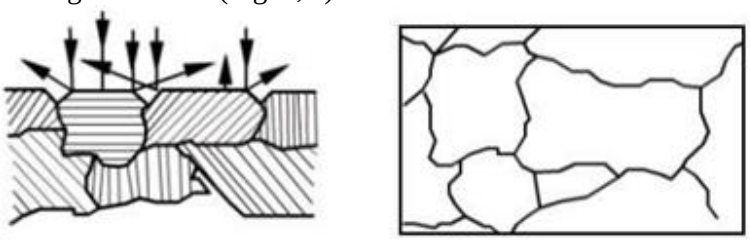
1) polycrystalline grain structure, including grain size, shape and distribution;

2) structural components of alloys.

A structural component is an element of a structure that looks like a homogeneous part during metallographic examination. Determining the microstructure of an alloy is a complex process, as it requires consideration of many factors [3].

When a microgrit is subjected to an etching process, different areas of its surface receive different degrees of treatment. For example, heavily etched areas of the grind appear darker under the microscope. This is because the intensity of the light reflected from these areas decreases. The more strongly the surface is etched, the more it scatters light, which in turn leads to less light entering the microscope objective (Fig. 2, a). This phenomenon makes it possible to visually distinguish different structural components of the alloy and better analyse their characteristics [3].

Thus, the etching process not only improves the visibility of the microstructure, but also contributes to a more detailed study of its components, which can be useful for assessing the material's properties and its behaviour under various operating conditions (Fig. 2, a).



a) ***b)***

Fig. 2. Detecting the microstructure of an alloy:
a – scheme of forming an image from the surface of an etched grind; b – etched sample with a homogeneous phase structure.

In a sample with a homogeneous phase structure, the boundaries between the grains are subjected to stronger etching compared to the volume of the grains themselves. As a result, microscopic examination reveals grooves that look like a dark mesh (Fig. 2, b).

To achieve this effect, various etching methods are commonly used, including chemical, electrolytic, and thermal [3-5]. Chemical etching involves the use of special solutions that selectively react with the material, emphasising the grain boundaries. Electrolytic pickling is carried out using an electric current, which allows for precise control of the processing depth. Thermal etching, in turn, can involve heating the material to improve microstructure detection.

These methods provide researchers with detailed information about the structure of a material, which is important for assessing its physical and mechanical properties and behaviour under different operating conditions [3-5].

There are two important effects of chemical or electrolytic pickling. Firstly, grooves are formed at the grain boundaries, which clearly mark the boundaries of the crystal structures. Secondly, there is a noticeable roughness of the grain surface, which can affect both different phases and grains of the same phase. The latter phenomenon occurs when the crystal lattice planes of different grains of the same phase coincide with the plane of the grind, which leads to a heterogeneous surface finish [3-5].

The grain boundary grooves are caused by the fact that the atoms in these areas have higher energy, making them more susceptible to chemical dissolution reactions. As a result, the grain boundaries, which are usually less stable, are exposed to more intense reagent attack, which causes grooves to form. This process is important for a detailed study of the microstructure of materials, as it allows us to identify the boundaries between grains and reveal their properties, which can significantly affect the characteristics of the finished product [3,4].

The unequal surface roughness of grains, both of different phases and of the same phase, arises from variations in chemical activity, which in turn are associated with different properties of these phases or the density of atoms packed on different planes of the crystal lattice. This means that the grain boundaries

usually have a higher activity than the central parts of the grains themselves, which leads to greater chemical dissolution during the etching process.

The atoms inside the grains have lower energy than the atoms at the boundaries, which results in a lower depth of relief on the grain surface. When examining samples in reflected light, the maximum optical contrast is observed between areas with different relief depths, in particular between grain boundaries and their volumes [3,4]. In contrast, the contrast between individual grains is much less pronounced due to slight differences in the depth of the surface irregularities.

Thus, the heterogeneous surface roughness of grains can serve as an important indicator of their structural and mechanical properties. This allows researchers to study the composition and behaviour of materials in more detail, and to understand how these factors can affect the overall performance and performance of products.

The contrast of the microstructure image can be significantly improved by 'colouring' the grains in different colours, which is achieved by creating a transparent oxide film on the surface of the grinding wheel. The thickness of this film varies depending on the grains, which leads to the appearance of different colours when observed in white light due to the interference phenomenon [3]. Such oxide films are formed as a result of heating a polished or lightly etched grinding wheel in an oxidising environment, which activates the oxidation process.

In addition, specific reagents have been developed for certain alloys that react with the sample material to form coloured films on the surface of grains of different phases. This makes it possible not only to enhance colour differentiation between different structures, but also to provide more information about their chemical nature and mechanical properties [3].

The use of such methods improves the ability to visualise the microstructure, which in turn contributes to more accurate material analysis. Thanks to the variety of colours, researchers can more easily identify structural features such as non-metallic inclusions, porosity or inhomogeneities in the composition, which are important aspects when assessing the quality and suitability of materials for various applications.

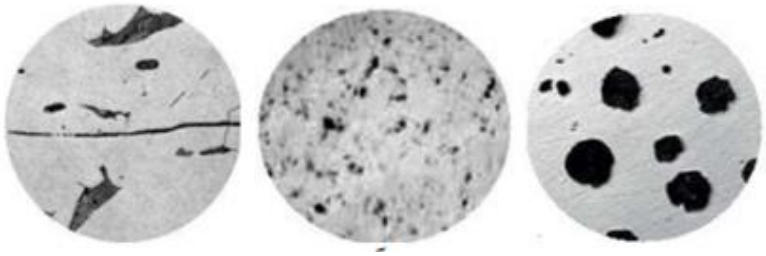
Thermal etching is an effective method that is carried out by heating the polished grinding wheel in a protective atmosphere or under vacuum. This technology makes it possible to create a relief on the surface, in particular grooves on the grain boundaries, which are formed by removing atoms from areas where their energy is high [3-5]. This is due to the increased mobility of atoms at high temperatures, which are at least 60% of the material's melting point.

Before proceeding to the heat-etching process, it is important that the abrasive is pre-polished. This can be done using electrolytic or chemical methods. This pre-treatment provides a more uniform and smooth surface, which in turn contributes to a sharper relief during thermal etching.

This pre-treatment provides a more uniform and smooth surface, which in turn contributes to a sharper relief during thermal etching. The resulting grooves and reliefs significantly improve image contrast during microscopic examination, allowing for detailed study of grain boundaries and their interaction. This method is particularly useful in metallography, as it allows the detection of microstructural features such as porosity, inclusions or inhomogeneities in the structure of a material, which is of great importance for assessing its properties and purpose.

It is recommended to begin the study of the macrostructure of materials by examining the unetched grind under a microscope [3-5]. This approach allows you to get the first idea of the structure of the material without the influence of chemicals that can change its natural characteristics. For example, in steels against a light background, non-metallic inclusions are clearly visible as dark areas. These areas may have different shades and even be coloured differently, indicating the presence of different elements or phases in the alloy (Fig. 3).

Examination of the unetched surface is an important step, as it allows us to identify defects such as inclusions, cracks or inhomogeneities that can affect the mechanical properties of steels. In addition, the visualisation of non-metallic inclusions helps to identify the presence of impurities that can affect the corrosion resistance and other material characteristics [4].



a) ***b)*** ***c)***

Fig. 3. Non-metallic inclusions in iron and carbon alloys (steel, cast iron): a – sulphurous iron (FeS); b – brittle oxides; c – graphite in cast iron

This preliminary study is the basis for further macrostructure analysis and provides valuable information for assessing the technological processes used in steelmaking and their behaviour in service. The collected data can be useful for further optimisation of the material composition and selection of optimal processing technologies [4].

By analysing the polished surface of the grind at low magnifications, important information about the material structure can be obtained. This allows you to assess the amount, type and uniformity of distribution of non-metallic inclusions that can affect its physical and mechanical properties.

In addition, this analysis can be used to investigate the porosity of the material, which is a critical indicator, as the presence of pores can indicate defects that occurred during manufacturing or processing. For example, shrinkage sinks resulting from insufficient mould filling during casting, or liquefaction resulting from uneven cooling, can have a negative impact on the overall condition and durability of the material.

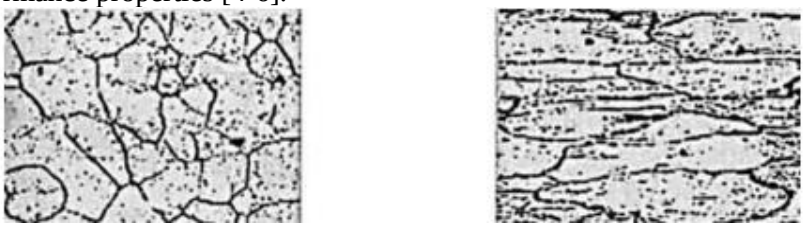
Identifying these defects is important for product quality control and further process optimisation [4-6]. The information obtained from the analysis helps in making decisions on possible adjustments to the manufacturing process, as well as in improving the materials used to create new alloys or products. It also helps to improve the reliability and safety of products in the field.

After studying the macrostructure parameters, the grind is pickled and then analysed again with a metallographic microscope to determine the microstructure. This process allows us to determine the number of structural components, their size, shape, colour, arrangement and homogeneity.

Most metals have a polycrystalline structure made up of individual grains, also known as crystallites. It is important to note that the size and shape of these grains largely depend on the technology used to produce the metal, as well as the nature of its subsequent processing. For example, casting, rolling, forging or extrusion methods can produce grains of different shapes and sizes (Fig. 4, a, b) [4-6].

The importance of these parameters cannot be underestimated, as they have a direct impact on the mechanical properties of the material. Determining the number and size of grains can give an indication of the strength, ductility, and overall resistance of a metal to external stress. For example, fine-grained materials tend to have better mechanical properties because their grains are more resistant to cracks and deformation.

The data obtained helps to identify patterns between technological processes and the characteristics of finished products, which in turn is the basis for optimising production, improving the quality of materials and enhancing their performance properties [4-6].



a) ***b)***

Fig. 4. Differences in the structure of iron during plastic deformation: a – initial state; b – change in the shape of material grains under conditions of significant plastic deformation.

In alloys, the structure is usually more multifaceted and complex than in pure metals. Alloys can have a different number of structural components, which significantly affects their physical and mechanical properties. For example, an alloy can contain only one structural component (Fig. 5, a), or consist of two different phases (Fig. 5, b), or even have a more complex multicomponent structure with three or more structural components (Fig. 5, c). [4].

a) ***b)*** ***c)***

Fig. 5 Alloy structures: a – 08PS steel, b – LS59-1 brass, c – B83 babite

Each of these phases may have different characteristics that determine their interaction, resistance to deformation, corrosion and other important aspects. The composition and the ratio between the structural components of an alloy can also have a significant impact on its use in industry and everyday life.

After a detailed study of all structural elements, you can proceed to both qualitative and quantitative microstructure analysis. Qualitative analysis allows for the evaluation of microstructure characteristics such as grain shape, size and type, as well as the identification of defects or inclusions.

Quantitative analysis, in turn, makes it possible to determine numerical parameters, such as the percentage of each structural component, as well as statistical indicators that characterise the distribution and structure of grains. This comprehensive approach to microstructure analysis is important for understanding the mechanical properties of a material and for predicting its behaviour in service [4-6].

3. The purpose of the article

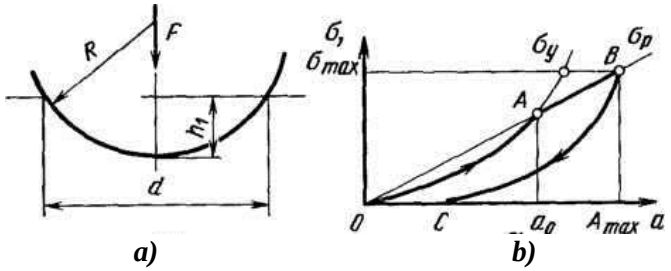
The purpose of the study: to investigate the change in the structure of the metal surface layer during water-pulse smoothing by means of metallographic analysis to determine the change in the shape and roughness of the deformed grains of the material under study. To achieve this goal, we need to solve the following tasks:

- to create the conditions for obtaining a micro-grind of the material under study;
- to compare the change in deformed grains after smoothing with the untreated surface of the material under study;
- analytically justify the nature of deformations depending on the type of load and material;
- taking into account the information received, draw conclusions.

4. Results of the researches

The surface layer formed during surface plastic deformation (SPD) of parts is the result of complex and interrelated processes occurring in the deformation zone and adjacent areas [4-6]. These processes include repeated elastic and plastic deformations, changes in the mechanical and plastic properties of the metal to be processed, friction, thermal effects, and transformation of the micro and macro structure of the material. An important aspect is the microgeometry of the machined surface, which affects the final properties of the part.

The main parameters that characterise the PDE include elastic and plastic deformations in the deformation cell, the contact area between the tool and the machined surface, and the force acting on the tool. This force causes stress, which in turn affects the amount of deformation and the formation of new microstructures in the metal surface layer. The microhardness of a metal is an important indicator, as it reflects its ability to resist further deformation and will affect the wear resistance of machined parts [4]. Thus, the control of PDE parameters and metal microhardness are key to achieving high machining quality and product life.



a) *b)*

Fig. 6. Deformation of metal when pressing a spherical indenter: a – imprint; b – dependence of elastic and plastic deformations on the indentation stress.

When a static or impact action is applied to the workpiece, a tool impression is first formed, which is then transformed into a series of adjacent impressions or marks. When a force F is applied to a solid ball (Fig. 6, a), it is pressed into the material: at the beginning of the process, the deformation is elastic, and with an increase in the force F, it turns into plastic (OAB line, Fig. 6, b) [4]. After the plastic deformation occurs, the reverse process occurs along the BC line, leaving an imprint of size d corresponding to the OS. The plastic deformation under the impression spreads evenly and reproduces the shape of the ball with minor distortions (Fig. 7) [4,5].

The microhardness of the material determines the resistance of the surface to tool indentation. Higher microhardness values reduce the size of residual impressions and reduce the depth of plastic deformation, which ensures greater material durability.

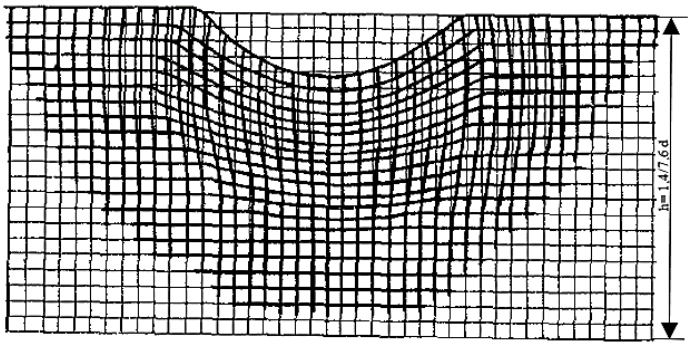


Fig. 7. Zone of plastic deformation propagation along the curvature of a rectangular mesh

The depth of the adhesive h is proportional to the depth of the print, i.e. h = mh1, where the coefficient m can vary from 2 to 20 depending on the processing conditions.

- The relationship between the diameter of the imprint d and the load F on the bullet during its penetration in the elastic and plastic regions is described by the Hertz and Meyer equations [5]:
- For the elastic region, the Hertz equation is used to determine the deformation of the material as a result of the elastic indentation of the ball.
- In the plastic domain, Meyer's equation is used to relate the diameter of the impression to the load when plastic deformation occurs.

Thus, when treating a surface with a ball, these equations allow us to estimate the nature of deformation depending on the type of load and material.

$$F = \frac{1}{3D\left(\frac{1-\mu^2}{E} + \frac{1-\mu_1^2}{E_1}\right)} d^3 \quad (1)$$

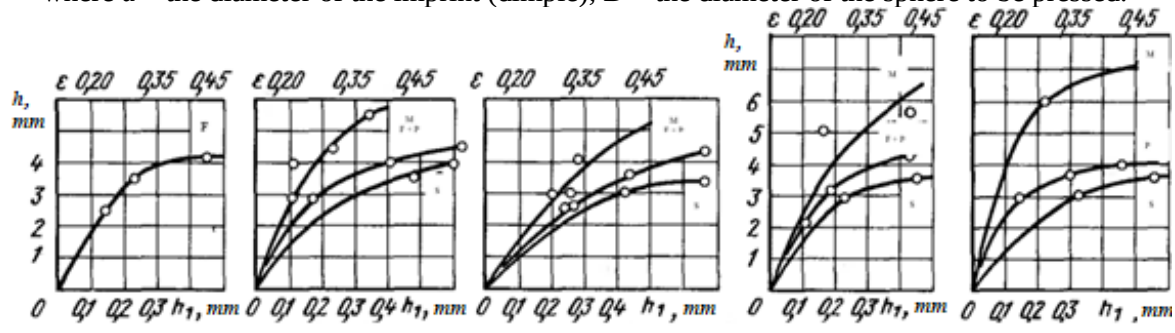
$$F = a \cdot d^n, \quad (2)$$

where D – the diameter of the ball; E, E_1 – Modulus of elasticity of the ball and the material being processed; $\mu; \mu_1$ – Poisson's ratio of ball and material; a, $n = 2$ – plasticity constants.

The above equations are valid for deformation conditions without friction, when the contacting bodies are isotropic, obey Hooke's law, the contact area is small, and the load is applied perpendicular to the machined surface. However, in PDE processes, the deformation conditions are much more complex [5,6]. In particular, the influence of friction, material anisotropy, and other factors can significantly change the way the tool interacts with the surface. Therefore, these formulas are of limited use for PDE, but they provide an insight into the main power relations that arise during this process. The degree of plastic deformation is equal:

$$\varepsilon = d/D, \quad (3)$$

where d – the diameter of the imprint (dimple); D – the diameter of the sphere to be pressed.



a) ***b)*** ***c)*** ***d)*** ***e)***

Fig. 8. Dependence of the depth of the riveted zone h from the depth of the print h_1 for carbon steels with different structures: a – iron; b – steel 35; c – steel 45; d – steel 60; e – U8; F – ferrite; M – martensite; P – pearlite; S – sorbite

For different PDE methods and processing conditions, the hardening factor can vary from 0.1 to 0.9, and for structural steels it is in the range of 0.3-0.7. Different structural components of a metal have different ability to strengthen. In particular, for the martensitic structure, the depth of the riveted zone is significantly greater than for other structures under similar processing conditions. On the contrary, sorbitol is characterised by the smallest depth of the riveted layer (Fig. 8) [5].

The microhardness of the metal plays a key role in the hardening process. Metals with a higher microhardness form a thinner riveted layer because they are less susceptible to plastic deformation. Structures with low microhardness, such as sorbitol, have less resistance to hardening, which leads to greater penetration of deformation into the metal [5, 6].

The degree of adhesion of different structures is determined by the relative increase in hardness. $\frac{\Delta HV}{HV}100$ and kept under the same conditions, the results shown in Figure 8 show that sorbitol has not only the lowest depth of adhesion, but also the lowest degree of hardening. The depth of the spalling h depends on the applied strain force F and is expressed as their ratio.

$$h = \sqrt{P/(2\sigma_T)}, \quad (4)$$

where σ_T – yield strength of the material.

For structural steels with an error of no more than ±10 % a fair ratio of $\sigma_T = HB/3$, so $h = \sqrt{3P/HB}$, $h = 1.5d$ (Fig. 9).

As the force F increases, the depth of the rivet increases as the higher pressure allows for deeper penetration of the tool into the material [5, 6]. The microhardness of the metal also affects this ratio: materials with high microhardness show a lower depth of pitting for the same level of strain, as they are more resistant to plastic deformation.

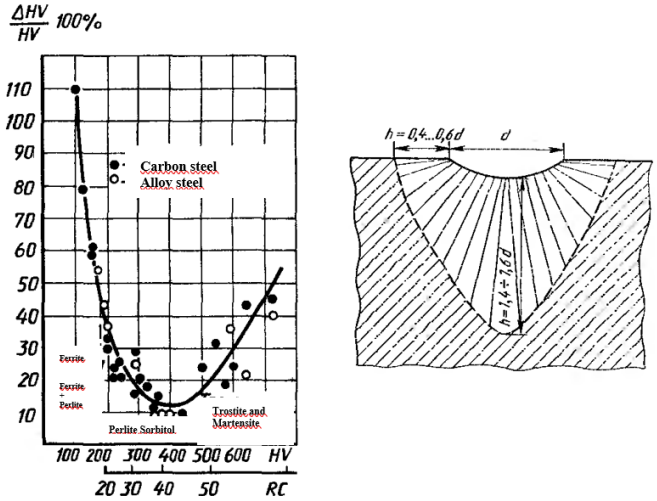


Fig. 9. Degree of maximum adhesion for metal structures of different hardness

When the same static load is repeatedly applied to the ball while it is being pressed into the same location, no significant increase in the size of the plastic impression is observed. This is due to the fact that static loading leads to the formation of a stable plastic deformation that is not subject to significant changes under repeated impacts.

Unlike static indentation, impact indentation of the ball causes significant changes. When the number of strokes is increased to 15-20, the print size can increase by 1.25-1.55 times for different processing conditions (Fig. 10). This growth occurs due to the accumulation of energy during impacts, which allows the material to move to new states of plastic deformation [5-7].

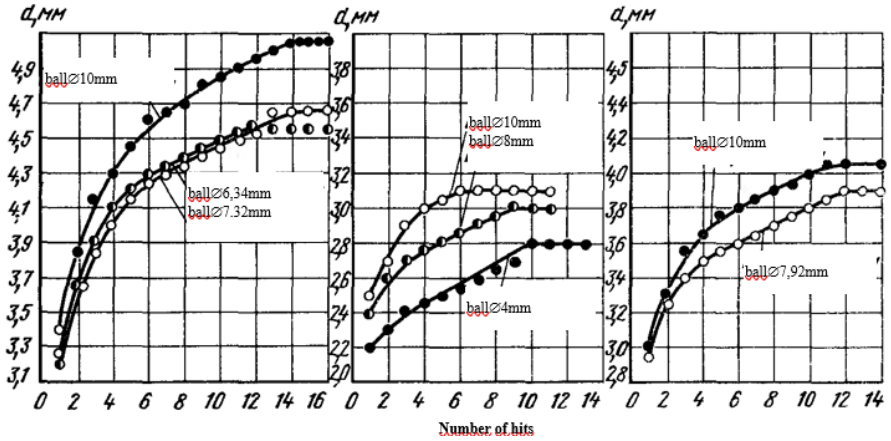
Interestingly, this increase in imprint appears to be smaller in the case of hard steels, as they have a high resistance to deformation. The diameter of the ball does not have a significant effect on the size of the imprint, which indicates that the main factor determining the behaviour of the material during impact indentation is its microhardness and mechanical properties: $d_{\max}/d \equiv 1.55 - HB/1000$.

The depth of the riveted zone formed during impact indentation of the ball is almost equal to the depth of the riveted zone obtained during static single indentation, provided that the diameters of the

impressions are equal. This indicates that the dependence of the parameters on the depth of the riveted layer, established for static indentation, can be correctly applied also under impact loading [5].

The impact load is determined by the impact energy transferred to the tool or workpieces and the deformation rate. Impact energy can be generated in various ways: for example, by imparting certain parameters to the flow of shot or a stream of steel balls using compressed air, liquid pressure, and centrifugal forces [6]. Other methods of generating impact energy are the use of vibrational movements of the working medium or the use of pneumatic and spring devices to transfer the impact load to the deforming tool (impactor).

Thus, the variety of ways to generate impact energy makes it possible to optimise material processing processes, in particular in the context of achieving the required depth of peening and surface hardening.



a) *b)* *c)*

Fig. 10. The nature of the propagation of the riveted zone under the surface of the print

During machining, the impactor, in addition to performing useful work to deform the material, also consumes energy for elastic rebound and overcoming friction forces [6]. For machining structural steels, the potential energy of the impactor should be 15-20% higher than the energy directly used for deformation. The energy expended on the elastic rebound of the E_B impactor depends on the mass, stiffness of the workpiece and the characteristics of its material, and can be 25-30% or more. Knowing the spring compression force F_{cp} and the stroke of the impactor X, it is possible to accurately estimate the potential energy of the impactor E_n and the impact energy E_u [6, 7].

$$E_{П} = F_{cp} \cdot X = E_{У} + E_{B} \,. \tag{5}$$

The optimum impact energy varies between 5-80 J depending on the diameter of the impactor (ball) and the hardness of the material being processed, with the range for structural steels being 15-50 J.

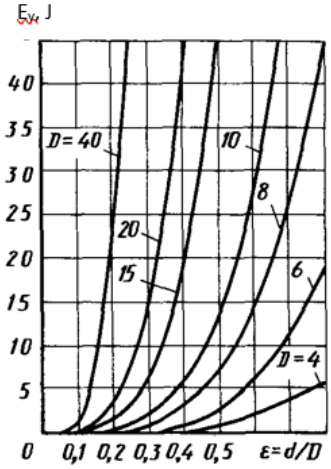


Fig. 11. Dependence of the energy of a single dynamic indentation Eu of a spherical ball on the degree of deformation e for balls of different diameters

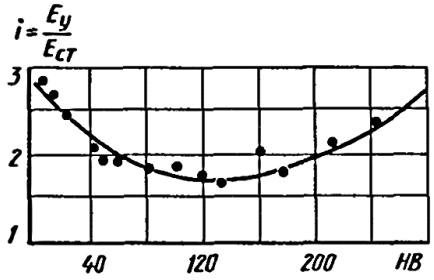


Fig. 12. Increase in indentation energy $J = J_y/J_{cm}$ under impact load compared to static load for materials of different hardness.

The physical essence of strain hardening is the mutual inhibition of dislocations when they increase significantly. The dependence of the stress required to continue plastic deformation on the dislocation density is expressed through the microhardness of the material [7].

$$\sigma_д = \alpha G b \sqrt{\rho}, \quad (6)$$

where $\alpha -$ is a coefficient that depends on the nature of the metal, its crystallographic orientation, structure and the contribution of various dislocation inhibition mechanisms to the overall hardening; *G*- is the shear modulus; $b -$ is the Burgers vector; is the dislocation density.

With an increase in the degree of deformation, there is an active increase in the density of dislocations. This phenomenon is related to the mechanisms responsible for the emergence and distribution of dislocations in the material, since a larger strain creates conditions for the generation of new dislocations and their accumulation in the structure [6,7].

Thus, changes in the dislocation density can significantly affect the mechanical properties of a material, including its strength and ductility.

$$\rho = \rho_0 + C\varepsilon^{\alpha}, \quad (7)$$

where ρ_0 – the initial density of deployments; C and α – coefficients and parameters that depend on the type of crystal lattice and other real deformation conditions; ε – the degree of deformation.

The usual values of these parameters for different types of metals. is: $\alpha = 1{,}0 \pm 0{,}5$, ρ_0 $(10^5 \dots 10^7)\ sm^{-2}$, $C = 10^{8\pm1}\ sm^{-2}$. In case of significant deformation ($\varepsilon \to 1$) The number of dislocations increases to their maximum possible values. $\rho = (10^{12} \dots 10^{14})\ sm^{-2}$.

The movement of dislocations in a crystal is affected by a number of energy barriers arising from the presence of other dislocations or their clusters [7]. The braking caused by the elastic interaction between dislocations is the main mechanism of strain hardening. This strengthening becomes particularly noticeable and sharply intensifies at the moment when the displacements in the planes intersecting the original sliding system cease.

Dislocation clusters play an important role in strengthening metals during deformation [6-9]. When several dislocation loops move along the sliding plane from a single source, and one of them stops due to an obstacle, then, when the second dislocation loop approaches the stopped section of the first one, the distortion in this area increases. This is due to the interaction of dislocations of the same sign, which creates additional distortions. The stresses arising from this interaction propagate around the close dislocation sites, expanding the distorted lattice zone and increasing the overall microhardness of the material [6, 8]. Thus, the interaction of dislocations contributes to the improvement of mechanical properties of metals during their deformation.

The effect of metal hardening is explained by the fact that the general stress circle arising from a large accumulation of dislocations can reach the source of deformation and affect it in the direction opposite to the external applied stress. This leads to an increase in the strength of the material, as internal forces are generated that counteract external loads.

During plastic deformation, due to the different orientation of the material grains in relation to the applied force and their heterogeneity in strength, different grains undergo deformation in different ways. These changes in the shape of the grains are accompanied by changes in their spatial position, which leads to displacement along the grain boundaries [7, 8]. This displacement becomes particularly important during deformation at high temperatures, when the role of grain boundary displacement increases. Under these conditions, increased slippage occurs between the grains along the boundaries, which is not accompanied by a change in the shape of the grains themselves. This slippage contributes significantly to the distribution of stresses in the material and can change its mechanical properties, such as ductility and strength. In particular,

the increased displacement along grain boundaries can lead to an improvement in the material's ability to withstand external loads without fracture.

The mechanism of deformation within grains varies depending on their structure. In small-angle boundaries with a dislocation structure, the displacement occurs mainly along the dislocation interface. At high temperatures, movement along grain boundaries becomes easier, since, in addition to the shear mechanism, the diffusion plasticity mechanism begins to play an important role, in which the main way of movement is the vacancy mechanism [7].

Strain hardening occurs in three stages due to the specific movement of dislocations during plastic deformation. At the first stage, dislocations are initiated, leading to the formation of new dislocation loops. At the second stage, they interact and accumulate, which leads to an increase in the number of dislocations in the material. At the third stage, intense dislocation displacement is observed, which in turn leads to a significant increase in material strength [7]. These stages are interconnected and determine the overall mechanical properties of metals during their deformation, which allows the development of new materials with improved characteristics.

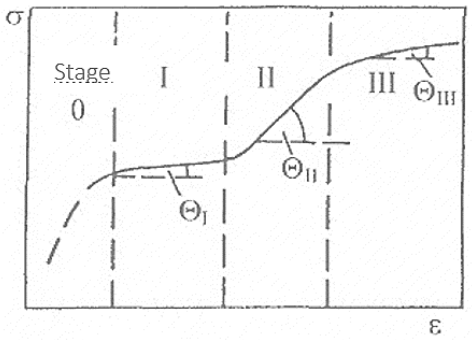


Fig. 13. Strain hardening curve of metal.

Stage I. At this stage, known as the easy slip stage, a low strain hardening coefficient indicates that dislocation movement occurs predominantly in one system. At a low density of initial dislocations, the number of barriers, the magnitude of elastic stress fields, and the number of thresholds on dislocations remain relatively small and grow weakly during deformation [8]. This means that the dislocations can move without significant obstacles at any given time, resulting in easy sliding of the material. Thus, at the first stage, there is a gradual development of plastic deformation, when the forces required for further displacement of dislocations remain quite low.

Stage II. At this stage, known as the multiple slip stage, the density of dislocations increases sharply, leading to a significant increase in the number of their intersections. As a result, the number of barriers increases and powerful clusters and tangles of dislocations are formed [8]. These factors, which inhibit the movement of dislocations, become key in the material hardening process. By effectively inhibiting the movement of dislocations, the strain hardening coefficient is significantly increased, making the material more resistant to further deformation. At this stage, the dislocations can no longer move freely, as at the first stage, and are forced to interact with each other, which increases the mechanical strength of the material.

Stage III. This stage begins when the stresses reach a level sufficient for active transverse sliding of dislocations. By the time it starts, sliding in all systems is already slowed down due to the presence of various barriers formed during the previous stages of deformation. At the third stage, the movement of dislocations becomes more complicated due to the massive intersection of their trajectories, which leads to intense interaction between dislocations [8]. During this period, the material experiences maximum resistance to further deformation, as complex dislocation structures arise that significantly increase its strength. The transition to cross sliding also increases the total number of barriers, which further strengthens the strengthening process.

Further deformation of the material occurs as the helical dislocations bypass the obstacles by means of cross-sliding. When this process begins, the strengthening factor decreases. There is a dynamic restoration of the structure, as the process of their annihilation (mutual destruction) begins due to the increased probability of meeting dislocations of opposite signs on the same plane [8-10].

Plastic deformation can occur both during the impact interaction of the tool with the workpiece and during static contact. Impact indentation requires 1.7-2.8 times more energy than static indentation,

depending on the hardness of the material. This is because at high loading speeds, plastic deformation occurs in a shorter time, and therefore more stress is required to change from elastic to plastic deformation.

When the impact speed increases to 7.8 m/s, the dynamic tensile strength of the steel increases significantly, but further increases in speed no longer have a significant impact on the tensile strength. The stress-strain relationship under dynamic loading is always greater than under static loading. While the elastic limit of impact remains almost unchanged, the yield and strength limits are significantly increased.

When the loading speed is increased to 100 m/s, for example, for Armco iron, the yield strength increases by 3.4 times, for steel 45 - by 3 times, and for St3 - by 2.8 times. The tensile strength for heat-treated carbon steels increases by 43% and for Armco iron by 55%. However, as the material hardness increases, the intensity of the change in these characteristics decreases, in particular, they change the least for high-strength steels.

The change in the mechanical properties of the metal in the surface layer during processing by the PDE methods is shown in Figure 15 [8]. For example, when diamond smoothing corrosion-resistant steel and aluminium alloy under optimal conditions, the tensile strength of the material's surface layer can double. During PDE, heat is generated by deformation of the metal surface layer and friction, which heats the workpiece, tool, working bodies and the environment. Strain heat is generated directly in the deformation zone, while frictional heat is generated at the contact surface. The heat source is local and is characterised by its effective heat output, i.e. the amount of heat generated per unit of time and its distribution in volume. The bulk of the heat is generated as a result of plastic deformation, which corresponds to the shape of the deformation centre (Fig. 16), and the process is accompanied by instantaneous local heating and rapid heat removal into the workpiece [8, 9].

The time of contact between the workpiece surface and the heat source depends on the speed of the heat source and its size in the direction of movement. The points lying on the X-axis have the longest contact time (when the source is moved along the X-axis). Points located at depth (z > 0) have a shorter contact time. For a point on the Z-axis that is on the edge of the source, contact with the heat will be instantaneous. If we denote by l the size of the source in the direction of its movement, then the heating time of each point on this axis can be calculated based on the speed of the source..

$$t = l/v. \quad (8)$$

Since the size of the deformation cell is influenced by numerous machining parameters such as pressure and tool size, the heating time depends not only on the tool speed but also on these parameters. If the temperature (Θ) resulting from the heat source is known, the heating rate is determined by the interaction of several factors: the intensity of heat generation in the deformation zone, the friction power, and the heat dissipation capacity of the material.

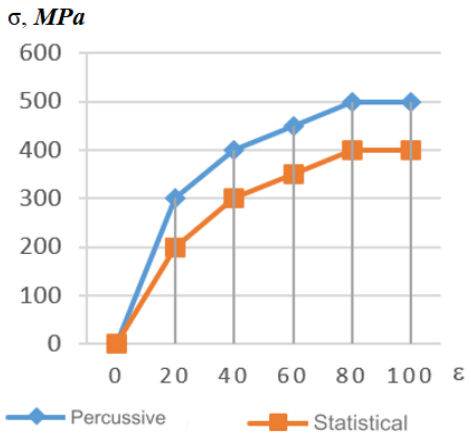


Fig. 14. Stress dependence on the degree of deformation for low-hardness steel under load

The heating rate depends on the local heat concentration and the pressure generated by the tool. The higher the pressure and the smaller the tool size, the more heat is concentrated in a small area, which accelerates heating [8]. This also affects the process duration: rapid heating can lead to localised overheating, which changes the mechanical properties of the material and can cause undesirable deformation or surface damage.

$$v_0 = \Theta/t. \quad (9)$$

Under intensive processing conditions, different local zones of the metal surface layer are heated to different temperatures depending on the processing method. For example, the temperature can reach 300-400°C during rolling, 600-700°C during smoothing, and 800-1000°C during impact methods. This wide temperature range is due to the different processing intensities, which include pressure, friction and deformation rate. These factors affect the depth of heat exposure and the structure of the material, which in turn affects its mechanical properties, such as strength, hardness and wear resistance [8].

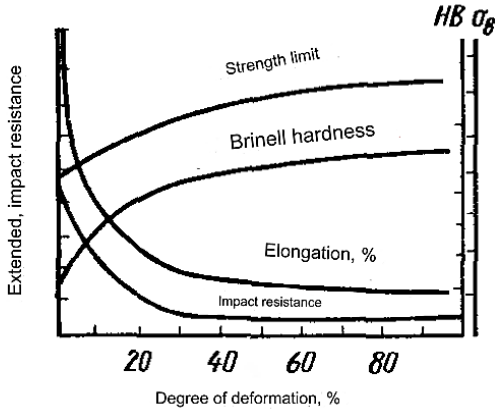


Fig. 15. Changes in the mechanical properties of the metal of the surface layer with the degree of deformation

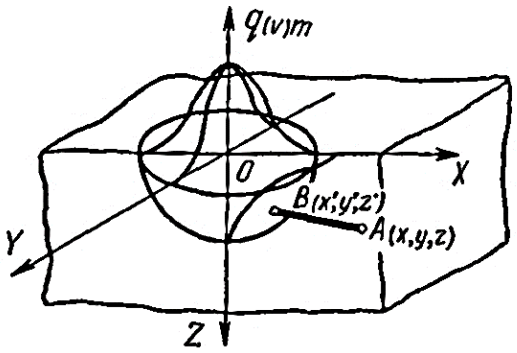


Fig. 16. Scheme of operation of an instantaneous heat source near the body surface

Such heating can cause thermoplastic deformations and other undesirable phenomena that reduce the surface hardening effect [8, 9]. Thermoplastic deformation leads to a sharp reduction in residual compressive stresses on the surface, and in some cases, to their replacement by tensile stresses. This can lead to the formation of secondary structures that impair the performance of the surface. The joints of different structures become stress concentrators, which increases the likelihood of fatigue cracks. To avoid these negative consequences, it is important to set the pressure and processing speed to a level that does not cause the surface temperature to rise above the permissible level for a particular material.

Surface plastic deformation (SPD) processing is accompanied by complex structural and phase changes characteristic of surface layer formation [9]. First, the metal grains are crushed into smaller blocks (polygonisation), which results in a mosaic structure. With the further development of displacements along the sliding planes, new, even finer grains are formed. In this process, the crystallites lose their globular shape, flatten and stretch in the direction of deformation. There is a sharp change in the ratio of their sizes, which leads to the formation of an ordered oriented fibrous structure. This structure has anisotropic mechanical properties: the ductility along the fibres is much higher than in the transverse direction, which affects the material's performance.

The main reason for hardening is an avalanche-like increase in the number of dislocations - defects in the metal lattice that accumulate near the shear zones and slow down in front of various obstacles arising during deformation [9]. Such obstacles can be crossed dislocations, where their trajectories intersect at a certain angle, or deformation bands. The crushing of the metal into small blocks between the sliding planes, their rotation, curvature of these planes and the accumulation of lattice defects contribute to the formation of additional irregularities. This, in turn, increases the slip resistance and leads to hardening of the metal.

When supersaturated solid solutions are tacked, they partially disintegrate, resulting in the formation of small particles of new structures. These particles, when they hit the sliding planes, block the movement of the shear and prevent deformation. In the case of deformation of steels with a ferrite-pearlite structure, the solid solution of α-iron and carbon decomposes, with iron carbides acting as obstacles in the form of small inclusions. Nitrides, nitrogen compounds, can also be formed. The increase in hardness during plastic deformation of steels with a martensitic structure is due to the partial transformation of residual austenite into martensite.

The specific volume of different structural components of the metal decreases in the following order: tetragonal martensite, cubic martensite, pearlite (sorbitol, trostite) and austenite. If structural changes occur during processing that lead to an increase in the specific volume (e.g., austenite to martensite transformation), residual compressive stresses are generated. In the reverse process, when the volume decreases, tensile stresses are generated [9, 10]. In addition, an increase in the number of crystal lattice defects and the formation of submicroscopic cracks also leads to an increase in the specific volume of metal. In the case of steels, this increase can reach 1.1%. This results in residual compressive stresses in the riveted area that can reach 1200-1500 MPa, depending on the material and processing method. The depth of propagation of these stresses is usually 10-50% greater than the depth of the hardened layer, and the maximum stresses are observed at or near the surface due to thermal effects [10].

Excessive machining forces can lead to over-peening, which results in dangerous microcracks in the surface layer. This also contributes to the detachment of metal particles, and the surface grains are flattened so much that they become almost indistinguishable. This results in a sharp increase in surface roughness. While defamation can be reduced or completely eliminated by annealing, defamation is an irreversible process. After over-coating, heating is not able to restore the original structure of the metal and its mechanical properties.

5. Conclusions

Surface plastic deformation processes during the machining of metal parts play a key role in the formation of a surface layer with improved strength and wear resistance characteristics. During surface plastic deformation, a complex interaction between elastic and plastic deformations, microstructure changes, friction and thermal effects occurs. Important parameters of surface-plastic deformation are the elastic and plastic deformations that occur in the contact zone between the tool and the surface being machined, as well as the microhardness of the material, which determines its resistance to further deformation.

The surface is strengthened by inhibiting the movement of dislocations and forming new microstructures that reduce the depth of plastic deformation. The Hertz and Meyer equations allow us to determine the deformation characteristics for the elastic and plastic domains, although the actual processes in surface-plastic deformation are more complex and take into account additional factors such as friction and material anisotropy.

The process of impact and static tool pressing affects the depth of the riveted layer and the microhardness of the material. Increasing the deformation force leads to deeper penetration of the tool into the material, which increases the strength of the machined parts. Strain hardening of metals is achieved through the accumulation of dislocations, which improves the mechanical properties of the material.

References

1. Paladijchuk, Yu.B., Telyatnik, I.A. (2022). Typy i konstruktsii vibrozbudzhuvachiv suchasnoho mashynobuduvannia [Types and designs of vibration exciters of modern engineering]. *Vibrations in Engineering and Technology, 4 (107).* 26–35. [in Ukrainian].
2. Telyatnik, I.A. (2023). Doslidzhennia poverkhnevoi plastychnoi deformatsii pry hidroimpulsnomu vplyvi [Study of surface plastic deformation under hydraulic pulse action]. *Engineering, energy, transport AIC, 1 (120).* 110–119. [in Ukrainian].
3. Veselovska, N.R., Paladijchuk, Yu.B., Telyatnik, I.A. (2022). Doslidzhennia mikrotverdosti poverkhni tsylindrychnoi detali pry deformatsiinomu protiahuvanni [Examination of microhardness of cylindrical part surface during deformation pulling]. *Engineering, energy, transport AIC, 3 (118),* 31–42 [in Ukrainian].
4. Iskovych-Lototsky, R., Veselovska, N. (2018). Automatic system for modeling vibro-impact unloading bulk cargo on vehicles. Proc. SPIE 10808, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments. 1080860 (1 October 2018). URL: https://doi.org/10.1117/12.2501526. (data zvernennya 30.09.2024). [in English].
5. Paladiychuk, Y., Telyatnik, I. (2023). Increasing the efficiency of choosing a hydraulic impulse drive with programmable control. *Agricultural engineering, 55,* 30–43. [in English].
6. Rostislav, Iskovych-Lototsky, Yaroslav, Ivanchuk, Yaroslav, Veselovsky, Konrad, Gromaszek, Ayaulym, Oralbekova (2018). Automatic system for modeling of working processes in pressure generators of hydraulic vibrating and vibro-impact machine. Proc. SPIE 10808, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 1080850 (1 October 2018). URL: https://doi.org/ 10.1117/12.2501532. (data zvernennya 30.09.2024). [in English].
7. Paladiichuk, Yu. B., Kordonskyi, V.A. (2020.). Obhruntuvannia mekhaniky ruinuvannia struzhky pry protiahuvanni tsylindrychnykh poverkhon z prypuskom [Justification of chip destruction mechanics when pulling cylindrical surfaces with allowance]. *Vibrations in Engineering and Technology, 4 (99),* 73–84. [in Ukrainian].
8. Iskovich-Lotockij, R.D., Ivanchuk, Ya.V., Veselovskij, Ya.P. (2014). Osnovi rezonansno-strukturnoyi teoriyi vibroudarnogo rozvantazhennya transportnih zasobiv [Fundamentals of resonance-structural theory of vibration shock unloading of vehicles]. *Science and transport progress. Bulletin of the Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, 5 (53),* 109–118. [in Ukrainian].
9. Paladiichuk, Y. (2021). Study of characteristics of growth formation after deformation strength during deforming strength. *Architecture Medical sciences Technical science Physics and mathematics, 2 (89).* 30–35. [in English].

10. Posviatenko, E., Posviatenko, N., Budyak, R., Shvets, L., Paladiichuk, Y., Aksom, P., Rybak I., Sabadach, B., Hryhorychen, V. (2018). Influence of a material the technological factors on improvement of operating properties of machine parts by reliefs and film coatings. *Eastern-European Journal of Enterprise Technologies, 5/12 (95),* 48–56. [in English].

МЕТАЛОГРАФІЧНЕ ДОСЛІДЖЕННЯ ЗМІНИ СТРУКТУРИ ДЕФОРМОВАНОГО ШАРУ МЕТАЛУ ПРИ ГІДРОІМПУЛЬСНОМУ ВИГЛАЖУВАННІ

Під час обробки матеріалів із застосуванням статичних або ударних навантажень спочатку формується відбиток інструменту, який згодом трансформується в ряд слідів, що з'єднуються. При вдавлюванні твердої кулі в матеріал, початкова пружна деформація переходить у пластичну з ростом навантаження. Пластичні деформації поширюються, залишаючи відбиток, розмір якого залежить від властивостей оброблюваного матеріалу.

Мікротвердість матеріалу є важливим показником його стійкості до вдавлювання; вищі значення зменшують розмір відбитків і глибину деформацій, підвищуючи довговічність матеріалу. Глибина наклепу, яка залежить від глибини відбитку, визначається коефіцієнтом, що варіюється залежно від умов обробки. Діаметри відбитків та навантаження на кулю описуються рівняннями Герца та Мейєра, які допомагають оцінити характер деформацій у пружній і пластичній областях.

Процеси обробки, які підлягають впливу тертя і анізотропії матеріалів, є більш складними, тому запропоновані рівняння мають обмежене застосування. Пластична деформація вказує на ступінь зміцнення матеріалу, який змінюється в залежності від структурних складових металу. Зокрема, мартенситні сталі демонструють вищу глибину наклепу порівняно з сорбітом.

Деформаційне зміцнення проходить три стадії: ініціацію дислокацій, їхню взаємодію та скупчення, а також інтенсивне зміщення дислокацій. Ці стадії взаємопов'язані та впливають на загальні механічні властивості металів. Зміщення по межах зерен грає важливу роль під час деформації за високих температур, що може змінювати механічні властивості матеріалу.

Крім того, дослідження підкреслює важливість розуміння мікроструктурних змін, спричинених пластичною деформацією під час процесів обробки поверхні. Аналізуючи взаємодію пружної та пластичної деформації, механізми деформаційного зміцнення та ефекти накопичення дислокацій, дослідження дають змогу зрозуміти оптимізацію механічних властивостей металів. Ці висновки є важливими для підвищення довговічності, зносостійкості та міцності оброблених компонентів, сприяючи розробці більш ефективних і надійних технологій обробки поверхні.

Ключові слова: *металографічне дослідження, деформований шар металу, структурні зміни, гідроімпульсне вигладжування, поверхнева обробка металу, пластична деформація, мікроструктура, механічні властивості металів, обробка тиском, технологічний процес.*

Ф. 9. Рис. 16. Літ. 10.

INFORMATION ABOUT THE AUTHORS

Yuriy PALADIYCHUK – Candidate of technical sciences, Associate professor of the Department of Agroengineering and Technical Service of Vinnitsa National Agrarian University (3 Soniachna St., Vinnitsa, 21008, Ukraine, e-mail: rewet@vsau.vin.ua, https://orcid.org/0000-0003-4257-9383).

Inna TELYATNIK – Recipient of the Third Educational and Scientific Level of Vinnytsia National Agrarian University (3, Solnychna st., Vinnytsia, 21008, Ukraine, e-mail: inna201098@gmail.com, https://orcid.org/0000-0002-2998-1506).

Marina KUBAI – lecturer at the Department of Ukrainian and Foreign Languages, Faculty of Management and Law. of Vinnitsa National Agrarian University (3 Soniachna St., Vinnitsa, 21008, Ukraine, e-mail: marinakubaj@ukr.net, http://orchid.org/0009-0000-5703-295X).

ПАЛАДІЙЧУК Юрій Богданович – кандидат технічних наук, доцент кафедри «Агроінженерії та технічного сервісу» Вінницького національного аграрного університету (вул. Сонячна 3, м. Вінниця, 21008, Україна, e-mail: rewet@vsau.vin.ua, https://orcid.org/0000-0003-4257-9383).

ТЕЛЯТНИК Інна Анатоліївна – здобувач третього освітньо-наукового рівня, Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна, e-mail: inna201098@gmail.com, https://orcid.org/0000-0002-2998-1506).

КУБАЙ Марина Григорівна – викладач кафедри української та іноземних мов факультету менеджменту та права Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна, e-mail: marinakubaj@ukr.net, http://orchid.org/0009-0000-5703-295X).